Superluminescent damping of relaxation resonance in the modulation response of GaAs lasers

K. Y. Lau, I. Ury, and N. Bar-Chaim
Ortel Corporation, 2015 West Chestnut Street, Alhambra, California 91803

Ch. Harder and A. Yariv
California Institute of Technology, Pasadena, California 91125

(Received 29 March 1983; accepted for publication 23 May 1983)

It is demonstrated experimentally that the intrinsic modulation response of injection lasers can be modified by reducing mirror reflectivities, which leads to suppression of relaxation oscillation resonance and a reduction of nonlinear distortions up to multi-GHz frequencies. A totally flat response with a 3-dB bandwidth of 5 GHz was obtained using antireflection coated buried heterostructure lasers fabricated on a semi-insulating substrate. Harmonic distortions were below 40 dB within the entire 3-dB bandwidth. These results are in accord with theoretical predictions based on an analysis which include the effects of superluminescence in the laser cavity.

PACS numbers: 42.55.Px, 42.60.Fc, 42.80.Sa, 42.60.Da

It is well established that most semiconductor lasers exhibit a resonance peak in their modulation characteristics before the final high-frequency falloff. The variation of the magnitude of this resonance among laser structures has been attributed to a variety of causes including the magnitude of the spontaneous emission factor and lateral carrier diffusion. The existence of this resonance peak limits the useful modulation bandwidth of lasers to considerably below the relaxation oscillation frequency where the response is relatively flat. Although equalization by external electrical circuit elements[1,2] or external light injection[3,4] has been suggested as means of suppressing the resonance, it is far preferable that one has a laser which possesses an intrinsically weak resonance. Lateral carrier diffusion, which plays a dominant role in some laser structures, may not be an effective means for suppressing relaxation oscillation, especially when the resonance occurs at high frequencies. The reason is that the effect of the diffusion is that of a low-pass filter on the modulation current,[5,6] thus creating a dip in the modulation response before the onset of the resonance peak and does not actually remove the resonance.[7,8] It was theoretically predicted[9] that lasers with a reduced mirror reflectivity possess a flat modulation characteristic, with modulation bandwidths comparable to lasers with regular cleaved-mirror lasers. This letter describes experimental results confirming the above theoretical prediction.

The lasers used in the experiment were buried heterostructure lasers fabricated on semi-insulating substrates[10] with a conventional length of 250 μm. The structure of this laser provides stable optical and electrical confinement, which reduce stray effects due to unstable optical modes or lateral carrier diffusion. In addition, its fabrication on a semi-insulating substrate considerably reduces the parasitic capacitance[11] which makes possible observation of the intrinsic response of the laser at high frequencies. Antireflection (AR) coatings were evaporated onto both mirror facets. Figure 1 shows the static light versus current characteristics of the laser before and after AR coatings were applied. Assuming that the internal distributed loss of the laser (including free-carrier absorption and waveguide scattering loss) is $\sim 70\ \text{cm}^{-1}$, the reflectivity was estimated from the increase in lasing threshold to be between 1–5%. Accompanying the increase in lasing threshold are the softening of the lasing transition and the increase in the number of lasing modes [Fig. 1(b)]. The multimode lasing spectrum in AR coated lasers has been observed before[12,13] and was explained by a theory involving effects of superluminescence inside the laser cavity.[14] An immediate consequence of the increase in the number of lasing mode is the increase in the spontaneous emission factor which has the effect of reducing the magnitude of the relaxation oscillation resonance.[15] This, in conjunction with additional effects due to superluminescence as described in Ref. 9, results in a modulation response which is completely flat up to multi-GHz frequencies.

Measurements at high frequencies were performed with

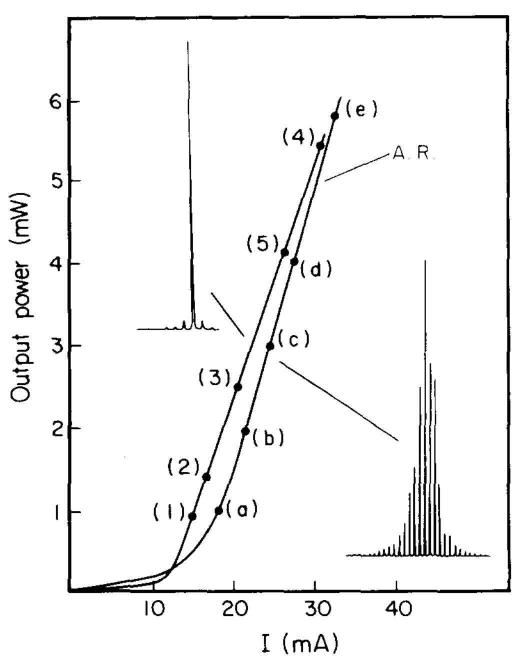

FIG. 1. cw light vs current characteristics of an uncoated and an AR coated laser. The static lasing spectrum of each laser is also displayed. The points on the curves indicate the bias currents at which high-frequency modulation measurements in Fig. 2 are performed.

the laser mounted on standard 50-Ω microstrip packages. No special provision was made for impedance matching. Microwave *s*-parameter measurements show that the amplitude of the modulation current driving the laser diode remains relatively constant, to within 2–4 dB, over the entire frequency range from 0.1 to 8 GHz. The photodiode used was a *p-i-n* photodiode having rise and fall times of ~ 60 ps. The 3-dB bandwidth of this detector was 2.5 GHz and the frequency response was calibrated up to 10 GHz using picosecond light pulses generated from a step-recovery diode excited GaAs laser. The finite width of the optical pulse, which was measured independently by optical second harmonic generation autocorrelation techniques to be 25 ps, was accounted for in the photodiode calibration. The frequency response of the laser was measured using a microwave *s*-parameter system (HP8350, 8410, and 8746B). The data were then normalized by the photodetector response. The result is shown in Fig. 2(a), where the different curves are obtained with the laser biased at the corresponding points indicated in Fig. 1 for the AR coated laser. A totally flat response with a 3-dB bandwidth of 5 GHz was obtained with this laser. The flatness of these response curves was in marked contrast to those commonly observed in regular injection lasers without coatings. A typical response of an uncoated but otherwise identical laser is shown in Fig. 2(b). All the lasers tested were from the same wafer and of the half-dozen or so lasers tested in each category, all displayed nearly identical characteristics as the shown in Figs. 2(a) and 2(b). It should be noted that the responses shown in both Figs. 2(a) and 2(b) have been normalized by the photodetector response. This is very important since the high-frequency falloff in the response of some photodetectors can equalize the relaxation oscillation resonance in the laser response, resulting in an observed overall response which is apparently flat.[11]

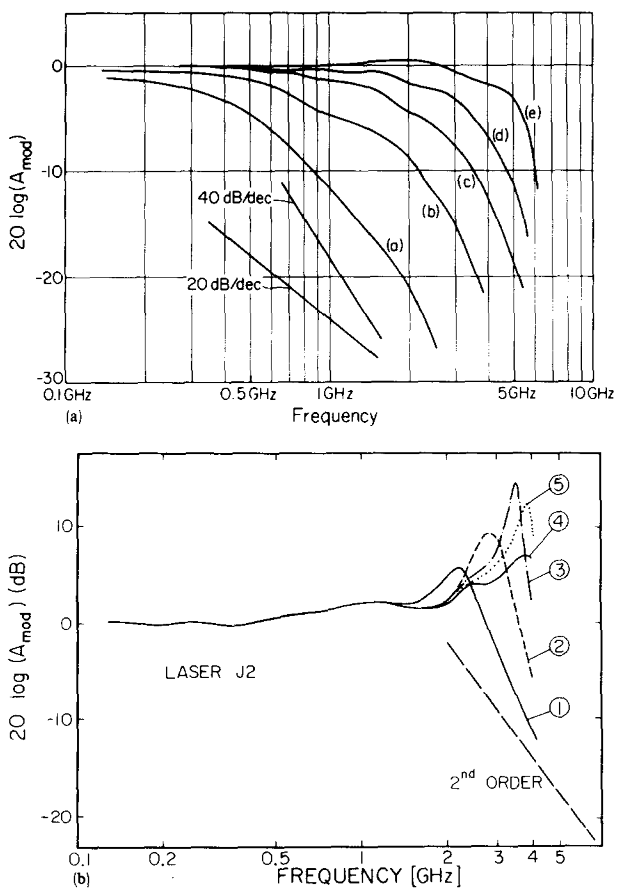

FIG. 2. (a) Modulation response of an AR coated laser at various bias currents shown in Fig. 1. (b) Modulation response of an uncoated but otherwise identical laser.

The calculations in Ref. 9 show that damping of the relaxation resonance occurs only when the facet reflectivity is reduced to a fairly low level, between 0.5% and 0.1%. That result was obtained assuming that only one facet was AR coated. In our experiments, both facets of the lasers were AR coated. Repeating the calculations as in Ref. 9 shows that in this case, a reflectivity in the vicinity of 1% is sufficiently low to manifest the damping effect. If, in addition, the increased amount of spontaneous emission due to the increased number of lasing longitudinal modes is taken into account, a reflectivity of 2–4% is already adequate. This is within the range of what can be attained by a single layer coating, and falls in the vicinity of the estimated reflectivities in the lasers used in our experiments.

As mentioned above, the relaxation resonance in the frequency response of lasers can be equalized by prefiltering the drive current[1,2] or compensated by the photodetector.[11] These methods, however, do not alter the fundamental properties of the laser under consideration and therefore cannot suppress the high level of harmonic distortion and intermodulation products, which are intrinsic to lasers with strong relaxation resonance.[16,17] These nonlinear effects can hamper the use of these lasers in multichannel analog transmission. Measurements of harmonic distortions under sinusoidal modulation were made of the lasers used in this study. The modulation current was adjusted at each frequency such that the fundamental of the modulation response of the laser remains constant. The corresponding modulation depth is fixed at 80% at all frequencies. This is in effect the electrical prefiltering scheme as described above. The harmonic content of the modulated output of an uncoated laser, as observed on a microwave spectrum analyser, follows the general trend as observed in a previous experiment.[17] At low frequencies (a few hundred MHz) the amplitude of the harmonics is very low, more than 60 dB below the fundamental. The amount of distortion increases, however, with increasing modulation frequency and reaches a maximum at around one-half of the relaxation oscillation frequency, at which the second and third harmonics are ~ 15 dB below the fundamental. The AR coated lasers, on the other hand, has a higher harmonic distortion than the uncoated ones at low frequencies, where the second harmonic is ~ 45 dB below the fundamental. This can be expected from the slight nonlinearity in the static light versus current characteristic due to a softening of the lasing transition [Fig. 1(b)]. However, the harmonic content of the modulated output does not increase significantly with increasing modulation frequency, remaining at < 40 dB below the fundamental over an entire modulation frequency range of 0.1–5 GHz. This result is a direct corollary of the absence of a strong relaxation oscillation resonance in these lasers.

In conclusion, it was demonstrated that the intrinisic modulation response of injection lasers can be modified by varying mirror reflectivities, with a resulting suppression of the relaxation oscillation resonance and a reduction of nonlinear distortions at multi-GHz frequencies. In addition, the flatness of the response extends the useful bandwidth of these lasers up to the point of the final high-frequency cutoff. Although experiments were performed on only one type of laser, it is expected that these results, which are manifested by basic superluminescent effects, apply to other laser structures as well.

This research was supported by the Defence Advance Research Project Agency.

[1]Y. Suematsu and T. Hong, IEEE J. Quantum Electron. **QE-13**, 756 (1977).
[2]J. Katz, S. Margalit, and A. Yariv, IEEE Electron. Devices Lett. **EDL-3**, 333 (1982).
[3]R. Lang and K. Kobayashi, IEEE J. Quantum Electron. **QE-12**, 194 (1976).
[4]D. Fekete, W. Streifer, D. R. Scrifes, and R. D. Burnham, Appl. Phys. Lett. **37**, 975 (1980).
[5]N. Chinone, K. Aiki, M. Nakamura, and R. Ito, IEEE J. Quantum Electron. **QE-14**, 625 (1978).
[6]D. P. Wilt, K. Y. Lau, and A. Yariv, J. Appl. Phys. **52**, 4790 (1981).
[7]K. Furuya, Y. Suematsu, and T. Hong, Appl. Opt. **17**, 1949 (1978).
[8]L. Figueroa, C. Slayman, and H. W. Yen, IEEE J. Quantum Electron. **QE-18**, 1718 (1982).
[9]K. Y. Lau and A. Yariv, Appl. Phys. Lett. **40**, 452 (1982).
[10]N. Bar-Chaim, J. Katz, I. Ury, and A. Yariv, Electron. Lett. **17**, 108 (1981).
[11]I. Ury, K. Y. Lau, N. Bar-Chaim, and A. Yariv, Appl. Phys. Lett. **41**, 126 (1982).
[12]R. G. Plumb and J. P. Curtis, Electron. Lett. **16**, 706 (1980).
[13]M. Ettenberg, D. Botez, D. B. Gilbert, J. C. Connelly, and H. V. Kowger, IEEE J. Quantum Electron. **QE-17**, 2211 (1981).
[14]K. Y. Lau and A. Yariv, Appl. Phys. Lett. **40**, 763 (1982).
[15]K. Peterman, Opt. Quantum Electron. **10**, 233 (1978).
[16]T. Hong and Y. Suematsu, Trans. ICEC Jpn. **E62**, 142 (1979).
[17]K. Y. Lau and A. Yariv, Opt. Commun. **34**, 424 (1980).

Internal photoemission from quantum well heterojunction superlattices by phononless free-carrier absorption

L. C. Chiu, J. S. Smith, S. Margalit, and A. Yariv
California Institute of Technology, Pasadena, California 91125

(Received 28 March 1983; accepted for publication 15 May 1983)

The possibility of phononless free-carrier absorption in quantum well heterojunction superlattices was investigated. Order of magnitude calculation showed that the absorption coefficient was significantly enhanced over the phonon-assisted process. Important aspects of the enhancement in the design of infrared photodetectors are discussed.

PACS numbers: 73.40.Lq, 72.20.Jv, 72.20.Dp, 79.60.Eq

Recently, a novel infrared photodetector using free-carrier absorption to excite electrons in a quantum well GaAs/GaAlAs heterojunction superlattice structure has been demonstrated.[1,2] In GaAs, the normal phonon-assisted free-electron absorption in a quantum well was found to be enhanced by a factor of 3–5 over its bulk value.[1] Despite this enhancement, the coefficient of free-carrier absorption, α, is still quite small. In view of this, the first detector working on this principle was designed to be an edge detector to provide a long interaction length.[2] Further investigation, however, revealed that phononless free-carrier absorption in a quantum well structure was possible, with further enhancement in the absorption coefficient.

In this letter we present an approximate calculation for $\alpha_f^{\rm pl}$ due to phononless free-carrier absorption in a quantum well. Estimated values for $\alpha_f^{\rm pl}$ were over an order of magnitude larger than the phonon-assisted case, but much smaller than the direct inter-sub-band absorption.[3] This is expected since the transition matrix element is now first order as compared to the second order phonon-assisted process, but the restriction on electron wave vector in the direction perpendicular to the superlattice plane renders it much smaller than the inter-sub-band absorption.

To demonstrate the effect of phononless free-electron absorption, an order of magnitude calculation for the absorption coefficient $\alpha_f^{\rm pl}$ in a single quantum well was performed. If the actual superlattice structure is such that the wells are effectively decoupled (which is desirable to minimize the dark current in a detector), then the present result will also be a reasonable estimate for $\alpha_f^{\rm pl}$ in such constructions.

Approximating the electron wave functions by

$$\psi_i = \left(\frac{2}{LA}\right)^{1/2} u_i(\boldsymbol{\rho}) e^{i\mathbf{k}\cdot\boldsymbol{\rho}} \sin\frac{\pi x}{L}, \tag{1}$$

$$\psi_f = \frac{1}{\sqrt{V}} u_f(\boldsymbol{\rho}) e^{i\mathbf{k}'\cdot\boldsymbol{\rho}} e^{ik_x x}, \tag{2}$$

where L is the width of well, $LA = V$ is the volume of the well $\boldsymbol{\rho}$ is the radius vector in the plane of the heterojunction (y-z plane), $\mathbf{k}$ the electron wave vector, u the periodic part of the Bloch function, and the subscripts i,f denote the initial and final states respectively. The interaction Hamiltonian is then given by

$$H_{fi} = -\frac{ie\hbar A_0\sqrt{2}}{2m_0 V}\int u_f^*(\boldsymbol{\rho}) e^{-i\mathbf{k}'\cdot\boldsymbol{\rho}} e^{-ik_x x}(\hat{e}_0\cdot\nabla)u_i(\boldsymbol{\rho}) \times e^{i\mathbf{k}\cdot\boldsymbol{\rho}}\sin\frac{\pi x}{L}\, d\boldsymbol{\rho}\, dx, \tag{3}$$

